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SOME APPLICATIONS OF GEOLOGY IN SOIL MECHANICS AND FOUNDATION ENGINEERING

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SOME APPLICATIONS OF GEOLOGY IN SOIL MECHANICS AND FOUNDATION ENGINEERING

Parker D. Trask,[1] and H. B. Seed,[2] J. M. ASCE

In 1952, a joint committee of the American Society of Civil Engineers and the Geological Society of America was formed to consider problems of mutual interest to these two groups. The formation of this joint committee marks the first official recognition by these two major national organizations of the wide variety of subjects which concern both geologists and engineers and reflects their increasing cooperation in recent years. More and more, the advantages of consulting an experienced geologist in the planning of large projects are being recognized by civil engineers, and the applications of soil mechanics in the study of earth and rock formations are being realized by geologists.

In view of this development of interest, together with the fact that this meeting of the American Society of Civil Engineers is being held in an area which is geologically young and unstable and consequently where a geologist can often be of assistance in engineering problems, it was hoped that a discussion of some applications of geology in soil mechanics and earthwork engineering problems, illustrated by examples taken mainly from the San Francisco Bay area, might be a pertinent topic for presentation at this Convention.

Both geology and soil mechanics have much to offer the civil engineer in the design and construction of foundations and other structures involving earth materials. The science of soil mechanics is primarily concerned with the effect of forces on the shape and equilibrium of soil masses. Consequently the soil mechanics approach to an engineering problem is by quantitative determinations of the forces acting and their effects on a soil mass in accordance with the established principles of mechanics. In order to assess the magnitude of the effects, an accurate knowledge of pertinent soil properties such as shear strength, compressibility characteristics, unit weight, water content, Atterberg limits, grain size distribution, etc., are required.

The geologist, on the other hand, when he works with the engineer, is concerned with qualitative or at best semi-quantitative determinations of the strength and other engineering aspects of the soil and rocks. His information is derived from his own or other existing knowledge of stratigraphy, sedimentation, petrology, dynamics of earth materials, structural geology, geomorphology, field mapping and geologic history. These subjects are complex in nature and since much remains to be

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learned about them, they are often difficult to apply to specific cases. In approaching a problem, the geologist must first, classify the rocks and earth materials into groups of similar origin and time of formation, and second, determine the extent to which they have been deformed or altered since they were formed. Having obtained this information he can then indicate the distribution of earth and rock materials in space, and hence can predict what is likely to be encountered at given positions below the ground surface. In civil engineering problems he can also indicate, by analogy with previous experience, the probable behavior of the rocks and sediments under the conditions proposed by the engineer.

Geology also has important applications in mining and petroleum engineering, in ground water investigations and in military problems. A geologist in any of these engineering fields must also engage in pure geology in order to develop information on the nature of earth and rock materials and on the processes that cause them to form and change. In this work the application of the principles of soil mechanics can help the geologist materially. This is particularly true in the studies of geomorphology and structural geology which are important tools in developing the geologic history of an area.

Some of the more important applications of geology in soil mechanics and earthwork engineering and an indication of some applications of soil mechanics in geology are discussed in the following pages.

Application of Geologic History in Determining Subsoil Profiles.

One of the main requirements in the design or construction of any civil engineering project is a subsoil profile showing the nature, properties and extent of the various soils underlying the area on which the structure is to be built. For this purpose borings are made at selected points and samples of soil from the borings are examined and tested. From the information thus obtained at selected points it is necessary to deduce the subsoil conditions over the entire area of the project.

When the project is confined to a limited area, the subsoil profile can often be reliably constructed by making borings sufficiently close together that interpolation between borings introduces very little error. However, when borings are more widely spaced, a knowledge of the geologic history of the area can be used to great advantage in reconstructing the probable distribution of the various soil strata.

One of the simplest applications of such knowledge may be illustrated by a recent incident when one of the writers was asked to review the foundation design for a highway structure. This structure was located in an old river bed and from the geologic history of the area it was anticipated that some peat would be encountered in the subsoil strata. It came as something of a surprise, therefore, to find that the borings showed no peat and the structure had been designed with a simple slab foundation. In this particular case, the consultant felt so sure that there must be some peat in the area that he requested an additional boring be made with himself in attendance. When peat was found in this boring, a comprehensive investigation was made and this showed the entire structure, some six hundred feet in length, had been designed to rest on a bed of peat. For some reason the peat had been

missed in the original boring investigation. In this particular case, the peat would have been discovered during construction but if the stratum had been several feet lower, the structure would have been completed and would subsequently have settled badly had not the probable existence of peat in this area been known.

Another example of the application of geologic history in the construction of a subsoil profile is illustrated by a recent job involving the construction of a preliminary soil profile parallel to the east side of San Francisco Bay. In the Bay, a series of valleys were formed in the sands and clays during the last glacial stage when sea level was 200 to 300 feet lower than it is now. Each stream coming from the mountains flowed over the previously deposited sediments as the sea level fell. The sediments being soft were easily eroded by these streams. The streams all flowed into a master valley that went around the south side of Yerba Buena Island and out to sea between the island and San Francisco. (See fig. 1). Subsequently, these valleys were filled with mud as sea level rose again. The valleys vary in width up to 1000 feet. Tributary valleys of any width can be expected at any place. The problem of the geologist is to work out the drainage pattern. If he has reason to believe a valley exists between two adjacent bore holes he should indicate the probable presence of the valley on his profile. As each valley in the Berkeley hills had previously been found to flow into one of these valleys in the bay, a valley was placed on the profile opposite one of the creeks even though no boring was available to indicate its presence. Subsequent drill holes proved the existence of the valley in the interval between the old borings.

On this same job, an interpretation of the geologic history of the San Francisco Bay area was used by one of the writers to predict the probable position of a granular soil and hence the length of piles required for one of the structures. The piles were to be driven across a section of the Bay extending for a distance of 500 feet between borings and the question arose whether adequate end-bearing for the piles could be developed in one of the older sediments below the bottoms of the mud-filled valleys. It was observed that the section in which the piles were to be driven was several hundred feet north of one of the mud-filled valleys. From geologic reasoning it was argued that the sediments beneath the Bay mud in this region would contain more gravel in the interval between bore holes than was found in the samples from the bore holes, and hence would provide equally as good if not better end bearing strength than at the places at which the borings were made. This reasoning was based on the fact that the land on the west side of major faults in the Bay area is moving northward with respect to the rocks on the east side of the faults. As has been pointed out by G. D. Louderback(1) rocks and soils on the west side of the Hayward fault on the University of California campus have moved at least one quarter mile to the north. Similarly the rocks on the west side of the San Andreas fault, likewise moved north with respect to the rocks on the east side during the 1906 earthquake. Hence it was argued that the sediments deposited in channels of the streams flowing from the Berkeley hills during the time of deposition of the older clays would

now occupy a position north of the axis of the channels of the streams that carved the valleys now filled with mud. As the sediments in stream channels are ordinarily much coarser than in the flood plains adjacent to the channel it was argued that the deposits along the supposed course of these older streams would have more gravel mixed with the sand and clay than at the sites of the bore holes drilled on either side of the valley. This line of argument seemed a little optimistic to all concerned, but additional borings subsequently confirmed the existence of gravel in the older formations in this area.

Since borings are often expensive, particularly if they are required in areas such as San Francisco Bay, the intelligent application of a knowledge of geological history can reduce the number of borings required and result in considerable saving. In other cases, where a choice is to be made between several possible sites, a knowledge of geology can often save time and money by excluding certain sites on the basis of unsatisfactory subsoil conditions.

The application of geologic knowledge in these ways and the predictions of a geologist regarding the distribution of soils and rocks have varying degrees of reliability, depending on the information available. The essential thing is for the geologist to know the extent of his reliability and to advise his engineering associates accordingly. Often he knows definitely what will be encountered at depths, and equally often, the best he can do is make an intelligent guess. But when he must guess he often can recognize the possibility of limiting factors that may embarrass the engineer in his operations. In such cases he should so advise the engineer in order that proper precautions can be taken or additional investigations can be made. For example in drilling tunnels through bed rock in San Francisco, the geologist knows that fractured and broken rock almost surely will be encountered, but without adequate surface exposures or drill holes he cannot predict accurately where dangerous broken zones will be found.

Applications of Geology in Determining Soil Properties and Foundation Conditions.

The properties of soils often depend, to a large extent, on their method of formation and subsequent geologic history. One of the more important factors determining the characteristics of a clay is its sensitivity to disturbance and one of the best-known theories(2) for the structure of clays describes how the structure and sensitivity will depend on the conditions under which the clay is formed. In support of this theory, it has often been observed in soil mechanics investigations that marine clays have high sensitivity.

The conditions to which a clay is subjected after its deposition can also have an important effect on its strength and compression characteristics. This is particularly well illustrated by the subsoil conditions in the vicinity of Boston, Massachusetts, where the geologic history has had an important effect on the type of foundations adopted for structures.(3)

During the last ice age this area was covered by a glacier, which scraped away soil above bedrock but then, in receding, deposited a

layer of glacial till over the rock. During the period of melting of the glacier, more than ten thousand years ago, the Boston area became covered by sea water as the glacier receded to the north. Rivers originating in the glacier transported fine particles of soil and deposited them beneath the sea, building up a layer of blue clay approximately 100 feet thick. Subsequently the relation between sea level and land was changed and the surface of this clay rose above the water. This exposure to the sun caused oxidation and desiccation of the clay at the surface, resulting in the formation of a stiff crust of clay and changing the color of this clay from blue to yellow. The effect of the desiccation extended to a considerable depth below the crust and had an effect equivalent to applying considerable pressure to the clay.

During this period too, vegetation and large trees grew on the ground surface. With the further passage of time some of the ground was covered by fresh water, resulting in the formation of peat and subsequently when sea water covered the area a bed of organic silt was put down above the peat. Finally a layer of soil has accumulated or in some places fill has been added so that a typical soil profile appears as in Fig. 2.

The organic silt and peat are so highly compressible that only small loads can be applied to them without causing excessive settlement. Thus it has become general practice in Boston to transfer building loads to the layer of firm yellow clay. This layer, hardened by desiccation, can safely support pressures from 4 to 6 ton/sq. ft. while the underlying blue clay from which the crust was formed, has an allowable bearing capacity of only 1 ton/sq. ft. However, the preloading of the upper part of this blue clay by desiccation has the beneficial effect of reducing its compressibility so that settlements of buildings founded on the crust are mainly caused by compression of the lower sections of the blue clay. It is interesting to contemplate what type of foundations might have been necessary for buildings in Boston had not the chance rising of the ground at some period in geological history resulted in the formation of the yellow clay bearing stratum and in the preloading of the blue clay. It is even more interesting to contemplate how the increased cost of these foundations might have influenced the development of the city. From a more practical standpoint, however, it is reassuring for engineers to know of the existence of the crust and the preloading effects and to be able to take advantage of these factors in designing building foundations.

The effect of geologic history on soil properties may also be illustrated by the subsoil conditions in San Francisco Bay. Here the final result is somewhat similar to that in Boston, but the geologic history is considerably more complex. However it may be described briefly as follows. The San Francisco region consists of two elevated areas separated by an intervening low area. The San Francisco hills on the west and the Berkeley hills on the east are composed of hard rocks covered by a soil mantle of varying thickness. In the intervening low area, which is occupied in part by San Francisco Bay, the old rocks have been covered by a series of much younger sediments consisting of sands, gravels, clays and mud. However, the contour of the bedrock is as irregular here as it is in the adjoining hills and thus the thickness

of the sediments covering it varies considerably in different parts of the Bay. The engineers took advantage of a high rock area in these sediments in constructing the San Francisco - Oakland Bay Bridge, as illustrated by Fig. 3. A buried ridge extends from San Francisco to Yerba Buena Island and this ridge provided a convenient and suitable foundation for the bridge foundations west of the island.

The sediments overlying bedrock in the Bay consist of five main formations: (1) the Alameda formation which varies in character between very firm clay, sandy clay, sand and gravel; (2) the San Antonio formation which consists of a series of layers of moderately firm clay, sand, and gravel; (3) the Posey formation which is a mixture of sand and sandy clay; (4) the Merritt sand; and (5) Bay mud. These formations are shown in Fig. 4.

The Alameda, San Antonio and Posey formations are predominantly alluvial deposits formed above sea level. They consist of material washed down from the surrounding hills. At times during their period of formation sea level rose or the land sank and a few layers of marine clay were deposited between the alluvial deposits.

Following the deposition of the Posey formation, the sea level sank 200 to 300 feet and the upper surface of the deposits was exposed to the air. During this period, the deep valleys mentioned previously were formed. Toward the end of the period of valley formation, the valleys were partly filled with wind-blown sand of the Merritt formation and sand was deposited on some areas of the more or less flat land between the valleys. Subsequently, the sea level rose gradually to its present position with the resulting deposition of the Bay mud, which fills up the old valleys and spreads as a blanket over the entire area of the Bay. A typical mud-filled valley is shown in Fig. 5. The thickness of the Bay mud thus varies considerably, a feature which affects considerably the planning of engineering construction in the area; in the valleys the mud may be 100 feet thick whereas in the flat areas between the valleys it is commonly only 10 or 20 feet thick.

With such a geologic history it would be presumed that the clay deposits in the Alameda, San Antonio and Posey formations would be preconsolidated to somewhat varying extents by desiccation occurring during and subsequent to their formation. The Bay mud, being permanently submerged would be expected to be normally consolidated. These facts have recently been established by tests on these soils made in connection with the proposed construction of additional Bay crossings.(4) In the San Antonio and Posey formations, the preconsolidation pressure was found to exceed the overburden pressure by amounts varying from 0.3 to 3.4 tons/sq. ft. Settlements in these clays due to an increase in load of, say, 1 ton/sq. ft. would therefore be small or negligible. On the other hand, for the Bay mud, the preconsolidation pressures corresponded closely to the overburden pressures and an increase in load of 1 ton/sq. ft. would therefore be expected to cause large settlements. Such settlements of the mud due to the construction of a mole causeway, weighing about 1 ton/sq. ft., for the San Francisco - Oakland Bay Bridge are shown in Fig. 5.

In connection with preconsolidation pressures, the ability of soil engineers to determine the preconsolidation pressures of clays from consolidation tests can be of assistance to geologists as an additional factor in developing the geologic history of an area.

Geologic knowledge can also be used to advantage in assessing the extent to which the engineering properties of soils are affected by mineralogic composition. For example, it is only in recent years that soil studies have been made by engineers to determine the characteristics associated with the clay minerals. Yet geologists have long been aware of the undesirable characteristics of montmorillonite and bentonite as compared with illite and kaolinite. The clay minerals have different abilities to absorb water and to change their properties by exchange of bases (cations). Kaolinite is the least susceptible and montmorillonite the most susceptible. Montmorillonite has the ability to absorb several times its volume of water and in so doing becomes very weak. Geologists have associated many slides with areas where montmorillonite is present.

The ability of montmorillonites to change their properties by base exchange also had early recognition in geology. For example, sodium montmorillonite is much less permeable than calcium montmorillonite. Knowledge of this principle was effectively used by C. H. Lee(5) in controlling salt water infiltration in the construction of Treasure Island in San Francisco Bay in 1938.

Further, the application of elementary principles of geologic processes in effecting changes in the chemical and mineralogic composition and the engineering properties of soils used in construction projects has been described in a recent paper by H. Forbes (6) on the geochemistry of earthwork.

Landslides

The problem of landslides is a subject of considerable interest both to the geologist and the soil mechanics engineer. In relatively homogeneous cohesive soils, slides can be predicted by soil mechanics studies. However, when the earth materials are irregular in character and rock strata or fault zones are present, slides are governed to a considerable extent by geologic criteria, and the conditions under which the earth will slide are more difficult to predict. This situation commonly is found in the San Francisco Bay area and in the Berkeley hills. Under variable conditions of this kind, often the only resource for the geologist or engineer is to make a careful survey of the configuration or morphology of the ground. An irregular hummocky surface is often indicative of previous slides and will thus serve as a warning that the area should be treated with caution. In other places the geologist may be able to warn the engineer of the presence of unstable formations.

The slide problem is of special importance in the Berkeley hills where numerous slides have affected highways and property during winters when the rainfall has been heavy. The hills north of the University of California, for example, form a very desirable residential area with a commanding view overlooking San Francisco Bay. Consequently, many homes have been built in this area in recent years.

Unfortunately, the slope of many of these hills represents the natural equilibrium condition and photographs of the hills, taken before the area became populated, indicate the existence of numerous former slides. Hence, when man cuts away the toe of a slope or adds fill, he upsets the equilibrium so that when a rainy period comes along, the land slides. He thus damages his own property and sometimes the property of other people as well. As the slides almost invariably occur after a period of heavy rainfall, the rain obviously is the trigger that sets the slide in motion, but the excavation or fill likewise are contributory causes, even though such work may have been done a considerable time previously. Thought has been given to public regulation of cuts and fills, but since it is not possible to indicate exactly how much earth material may be removed or added before the land will slide during a period of heavy rain, and since ground conditions differ so much from area to area, it is difficult to set arbitrary limits as to the extent to which any hilly area may be excavated or loaded with safety. However, in areas which are known to be critical, great care should be taken in changing the natural conditions of load.

Soil mechanics investigations of landslides in the past thirty years have also served to throw some light on geological formations and occurrences which might otherwise be called geographical accidents. In this respect, engineering studies have been of considerable assistance to the geologists. For example, engineering investigations have shown that failure of an embankment consisting of a clay soil or underlain by a clay soil usually occurs by the sliding of a mass of earth along a surface which in section corresponds approximately with the arc of a circle. This is particularly well illustrated by a slide which occurred in the bank of the river Ouse in England, described by W. H. Ward.(7) The river erodes the toe of the bank at some sections and when the bank is steepened sufficiently that a critical slope is reached, a failure occurs. Such a failure is shown in Fig. 6. There is a depression of the ground at the top of the slope and a heaving of the toe until equilibrium is again established. Knowing the form of the failure surface and the strength of the soils in an embankment, the possibility of such a slide occuring may be predicted. The weight of the soil mass located above any potential sliding surface tends to cause rotation of the mass about the axis of the cylindrical surface on which it slides. This rotation is resisted by the shear resistance of the soil along the potential sliding surface. The factor of safety against sliding along any particular surface is determined by the ratio of the maximum resisting moment to the overturning moment.

It is evident that a slide may be induced in a previously stable slope either by an increase in overturning moment, as may be caused by erosion at the toe, or by a reduction in the shear strength of the soil. Such a reduction in shear strength may result from an increase in pore-water pressure owing to excessive rainfall. At any point in a soil mass, the pore-water pressure and the pressure between the grains must together support the applied pressure. Thus, if the applied pressure does not change, any increase in pore-water pressure causes a corresponding decrease in the intergranular pressure. Since the shear

resistance of a soil is mainly due to friction between the grains, a reduction in intergranular pressure causes a decrease in shear resistance. The increase in porewater pressure resulting from heavy rainfall is mainly responsible for the large number of the slides which occur in the Berkeley hills of California. A typical slide in this area, which occurred in the winter of 1951 near Orinda, is shown in Fig. 7. Such slides can often be stabilized by relieving the pore-water pressures—a solution which has led to the development in this area of the Hydrauger method of installing horizontal drains for the stabilization of slides.

An excellent example of the manner in which a series of slides, resulting from a reduction in shear strength of soil, has affected a geologic formation and caused a series of "geographical accidents" is provided by a study of Folkestone Warren on the south coast of England.(7) A section through the Warren, which is about 3 miles long and 1/4 mile wide is shown in Fig. 8. In the steep cliff, about 500 ft. above sea level, on the land-side of the Warren, the strata consist of chalk overlying Gault clay and Lower Greensand, which is a soft sandstone. In the Warren itself, Gault clay is overlain by an erratic accumulation of chalk as a result of a number of major slides which have occurred in the Warren since the middle of the eighteenth century in the years 1765, 1800, 1839, 1877, 1896, 1915 and 1937. The generalized section through some of these slides, developed by W. H. Ward and shown in Fig. 8, indicates how the position of the chalk may be attributed to slides along cylindrical surfaces. It will be noted that for each slide a large part of the sliding surface is along the boundary between the clay and the sandstone.

In the 1937 slide, which has been studied extensively, it was observed that the front part of the sliding mass moved forward about 70 feet with only a slight deformation. This type of movement, together with the location of the sliding surface, led K. Terzaghi(8) to explain the probable cause of the slides:

"Such a movement would not be conceivable unless the resistance against sliding along the base of the moving section of ground was very low. Furthermore, the slide was not preceded by a change of the external conditions for the equilibrium of the slope. Hence, we are compelled to assume that the resistance against sliding has decreased, which can be accounted for only by an increase of the hydrostatic pressure on the base of the sliding body.

"The borings, made in 1939, show that the piezometric surface for the Lower Greensand was located at elevations up to 27 feet above sea level. These elevations are subject to seasonal variations and to variations within a longer period, caused by variations in the average rainfall. However, in the Warren, the rainwater has no opportunity to get into the Lower Greensand from above, because the Greensand is covered with a blanket of Gault clay having a very low permeability. The variations of the piezometric heads can be caused only by similar variations in the elevations of the water table in that region where the Greensand emerges at the surface. This region is located many miles north of the Warren.

"The fact that the major slides in the Warren occurred once every 19 or 20 years suggests that the movements were due to corresponding maxima in the amount of rainfall in those regions where the aquifer located beneath the slide area reaches the surface. In agreement with this assumption the Warren slide of 1937 was preceded by abnormally heavy rainfalls, 'between 15 and 16 inches of rain falling during the first three months' (Seaton, 1938, discussion by Ellson on p. 438)."

A particularly interesting type of slide occurs when the intergranular pressure in a soil is reduced, by some external cause, to such an extent that the shear strength is almost completely destroyed. In such a case, since the soil has practically no shear strength it is said to liquefy, and a flow slide results. The explanation of these slides was advanced by A. Casagrande(9) and is based on the decrease in volume of a loose granular soil when it is deformed. Any deformation of such a soil causes the soil grains to move into a more dense condition, and the air or water occupying the void space has to move out of the soil. If the voids are filled with air, the air can normally escape sufficiently rapidly that the only effect is a decrease in volume of the mass. However, if the voids are filled with water, the resistance to movement of the water through the voids is sufficiently great to prevent an instantaneous decrease in volume and for a small interval of time, the grains tend to move into a more dense condition but are prevented from doing so by the inability of the water to escape. During this small interval of time, therefore, there is little contact between the grains and all of the applied pressure is carried by the pore-water, so that the shear strength of the soil is destroyed and the mass will liquefy and flow until the movement is arrested by the drainage of excess water. By the time this has occurred, however, the mass has usually spread laterally until its surface is practically horizontal.

The deformation necessary to cause such a slide may be produced by vibrations due to blasting or pile-driving. It may also be caused by earthquakes or natural disturbances such as those which have resulted in the well-known flow slides along the coast of Zeeland. In this region a total of 229 slides, involving the movement of quantities of sand varying from 80 cu. yds. to 3 million cu. yds., were reported in the period 1881 to 1946.

Probably the largest flow slides which have been reported are those which occurred in Kansu Province, China, as a result of an earthquake in May, 1922. These amazing occurrences have been described by Upton Close and E. McCormick(10) under the title, "Where the Mountains Walked." The landslides occurred in the heart of loess country, causing destruction to ten large cities, numerous villages, many of which were buried or carried away, and the loss of about 100,000 lives. In one valley the only three survivors and their farmstead were carried about 3/4 mile on one of the streams of earth, while a section of the highway was transported for almost a mile before being set down on a heap of loose loess. As A. Casagrande(11) has pointed out, even if the soil is not saturated, when such a large mass is involved, spontaneous liquefaction may occur due to the time required for excess air to escape from the voids.

An interesting flow slide in an engineering structure is that which occurred during the construction of the Fort Peck Dam causing about 6,000,000 cu. yds. of soil to spread itself over the valley floor. This slide has been attributed by A. Casagrande(11) to liquefaction of a saturated loose sand section of the dam resulting from deformations caused by yielding in a weak stratum of shale in the foundation. This yielding has been attributed to the presence of weak bentonitic layers, containing montmorillonite, in the Bearpaw Shale underlying the dam.

Applications of Geology in Engineering Construction in Rocks

The study of the characteristics of hard rocks is somewhat beyond the scope of soil mechanics. However, the soil mechanics engineer is frequently called upon to investigate the properties of soft rocks, such as shales, and in foundation engineering, a knowledge of the characteristics of hard rocks is often required. It is desirable that a foundation engineer should have sufficient knowledge of geology to make reliable decisions concerning rocks on small jobs or in cases where time does not permit consultation with a geologist. On major projects involving construction in rocks, such as tunnelling and the preparation of dam foundations, the advice of a geologist or of geologists is invariably obtained.

In such cases the geologist, because of his knowledge of the probable distribution and characteristics of rocks, is particularly helpful in the preliminary planning and design stage. He can help materially in planning drilling programs and can point out areas where engineering problems may be encountered. For example in selecting dam sites he can point out the presence of weak or strong zones and indicate areas where escape of water or swelling of shales may be a problem; in tunnelling, he can advise the engineer on the possibility of encountering faults or fractured zones, of excessive water in-flow and on the pressures of the rocks on the tunnel lining. In all these problems, one of his main functions is to point out the existence of limiting or embarrassing factors which the engineer might not recognize.

This particular function may be illustrated by a recent case in which one of the authors was involved. A water tunnel driven through rock in an arid region was designed to operate under a hydrostatic head. The country rocks were fairly solid granite broken by two sets of intersecting joint systems, which in some sections of the tunnel, were each inclined at about 45° to the vertical axis of the tunnel.

The tunnel was designed to have a limited amount of lining, but after it had been driven, the engineers decided to ask the opinion of a geologist as to the stability of the wall rocks. Though the rocks were stable in the dry state, it appeared reasonably certain that the filling of the joint systems with water under hydrostatic pressure would cause collapse of the tunnel roof in places, particularly in those sections where the joints intersected at right angles a short distance above the axis of the tunnel. Hence, it would be necessary to provide more lining than had been originally planned.

Since much has been written on the applications of geology in hard rock engineering, in the selection and preparation of dam foundations,

and in the design and construction of tunnels, it is not intended to discuss these matters further in this paper. However, it might be pertinent to point out that geologic information can be used to advantage in determining the locations of desirable borrow areas and of rocks suitable for the preparation of aggregates and rip-rap. The geologist can also assist the engineer in indicating the presence and extent of weathered rock zones. The significance of rock weathering as a factor in the cause of landslides in the San Francisco area has been discussed in a previous paper presented to the ASCE by H. Forbes.(12) Weathering in this region can also lead to misconceptions of the adequacy of an area for supporting building foundations and to difficulties in planning excavations. For example, the weathering of chert on the slopes of hills has, in some places, caused soft clay to form beneath the surface of the ground. Where the chert is exposed in outcrops at the surface it is a firm dense rock that appears capable of supporting heavy loads, yet immediately adjacent to these outcrops the chert may be weathered to a clay soil which can support only moderate loads and which may slump badly when exposed in excavations.

A phenomenon associated with weathering called "case hardening" can also lead to mistaken interpretation of the strength of sandstone in the San Francisco Bay area. Many of the sandstones are porous and contain ground water during the wet winter season. During the summer months this water evaporates and leaves a precipitate of silica and other minerals in the interstices of the rocks near the surface. The surface rock thus becomes cemented and hard, giving an impression of great strength, whereas a short distance below the surface they are soft and not well cemented. The possibility that such a condition may exist is a factor to be considered in dealing with massive sandstones.

Conclusion

In this paper an attempt has been made to show some applications of geology in soil mechanics and foundation engineering. It has not been the intention of the authors to discuss all possible applications, or to describe fully all the applications mentioned. However, it is hoped that sufficient information has been presented to show that the soil mechanics and foundation engineer can benefit considerably from a knowledge of geology or from the cooperation of a geologist and that soil mechanics studies can be used to advantage in geology.

It is desirable, therefore, that geologists and soil mechanics should be familiar with fundamental concepts relating to both fields. However, few individuals are likely to be competent to handle all aspects of both fields. Thus, it would seem desirable that a specialist in one of these fields should be capable of handling routine problems in the other field but should recognize his limitations and know when to call in a specialist in that field to assist him. Further, when the services of a geologist are required on an engineering project, he should be an engineering geologist who is familiar with the problems and difficulties of the engineer.

It is hoped that this paper may stimulate further discussion and consideration of the applications of geology in soil mechanics or of soil mechanics in geology and may contribute in some small measure to a better understanding and a closer cooperation between workers in these related fields.

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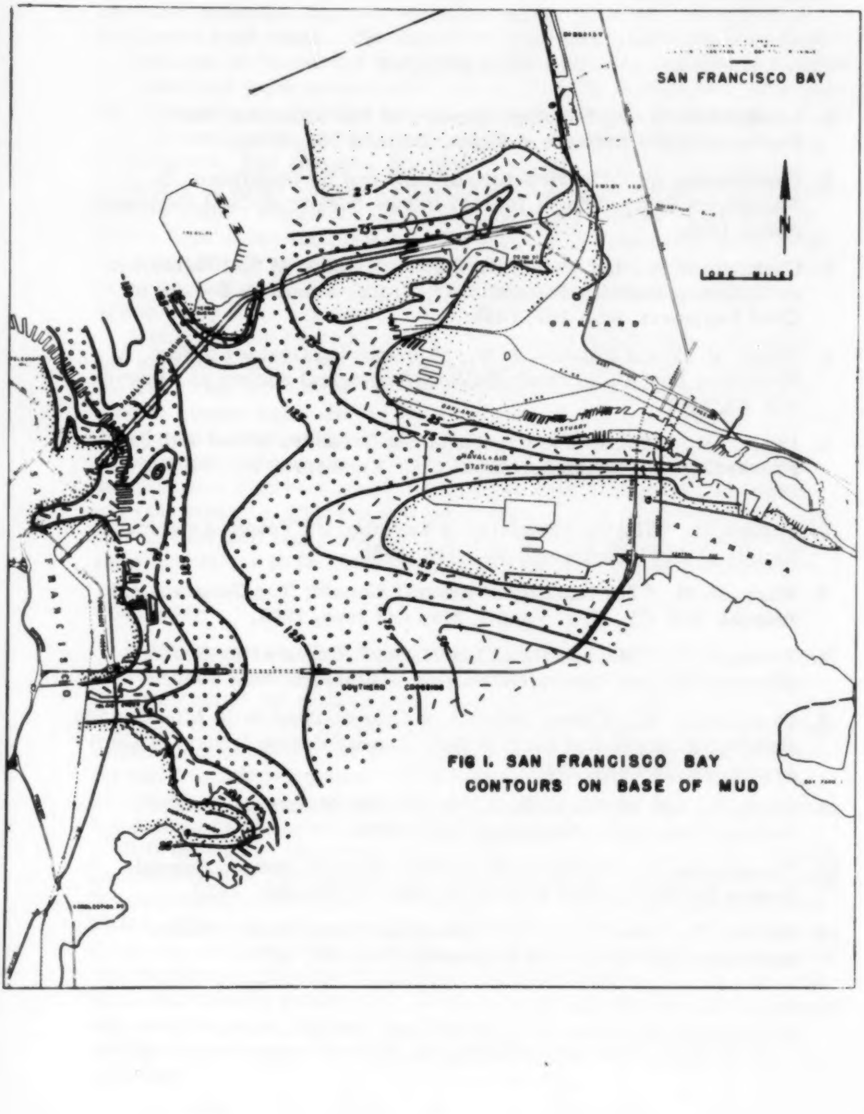

FIG I. SAN FRANCISCO BAY
CONTOURS ON BASE OF MUD

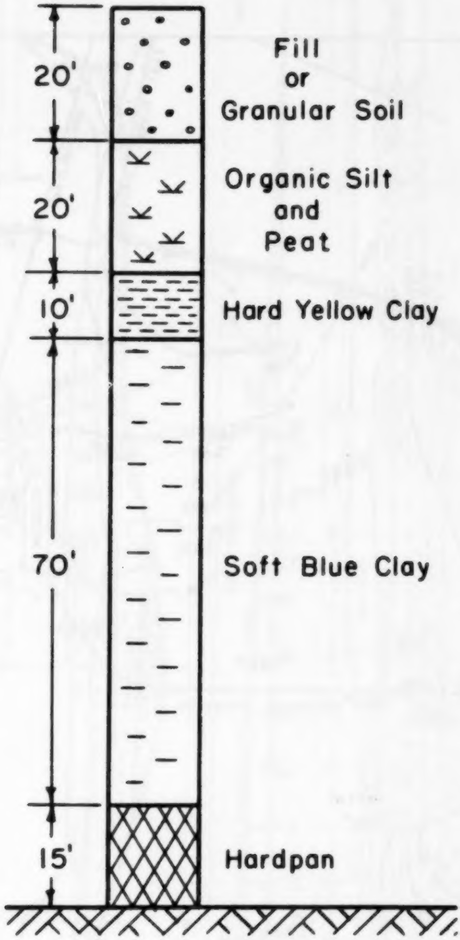

FIG. 2. TYPICAL SOIL PROFILE
IN THE BOSTON AREA

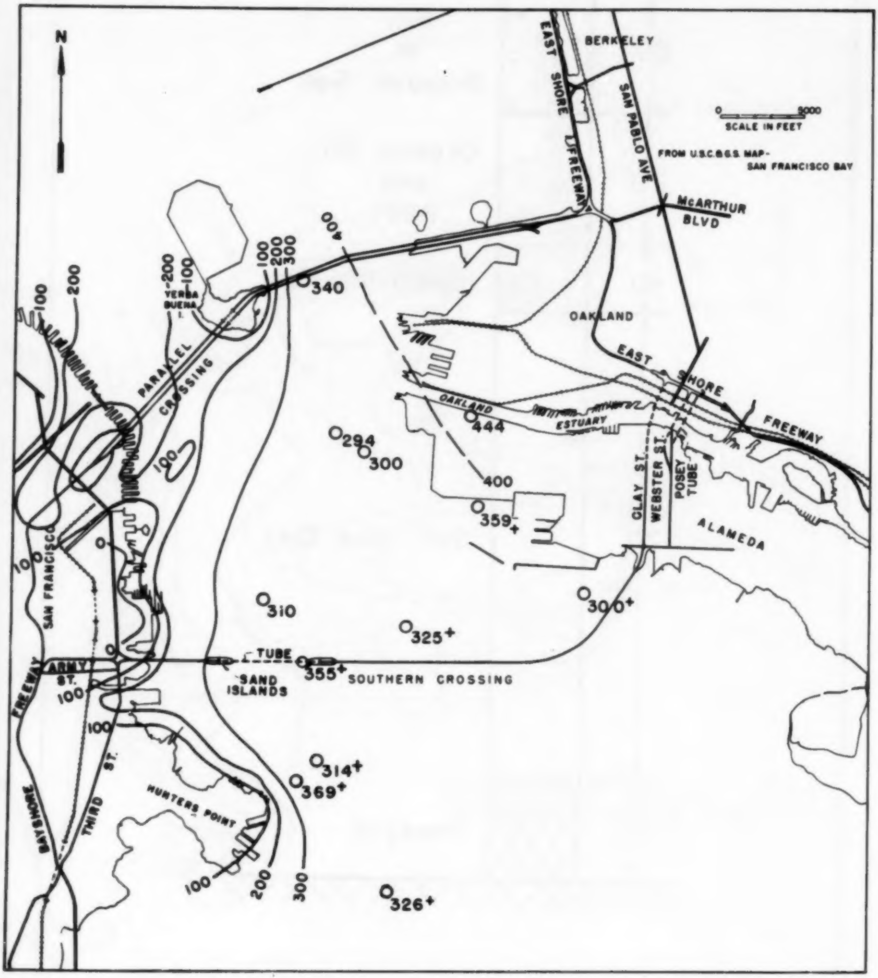

FIG. 3. BEDROCK CONTOURS,
SAN FRANCISCO BAY, CALIFORNIA

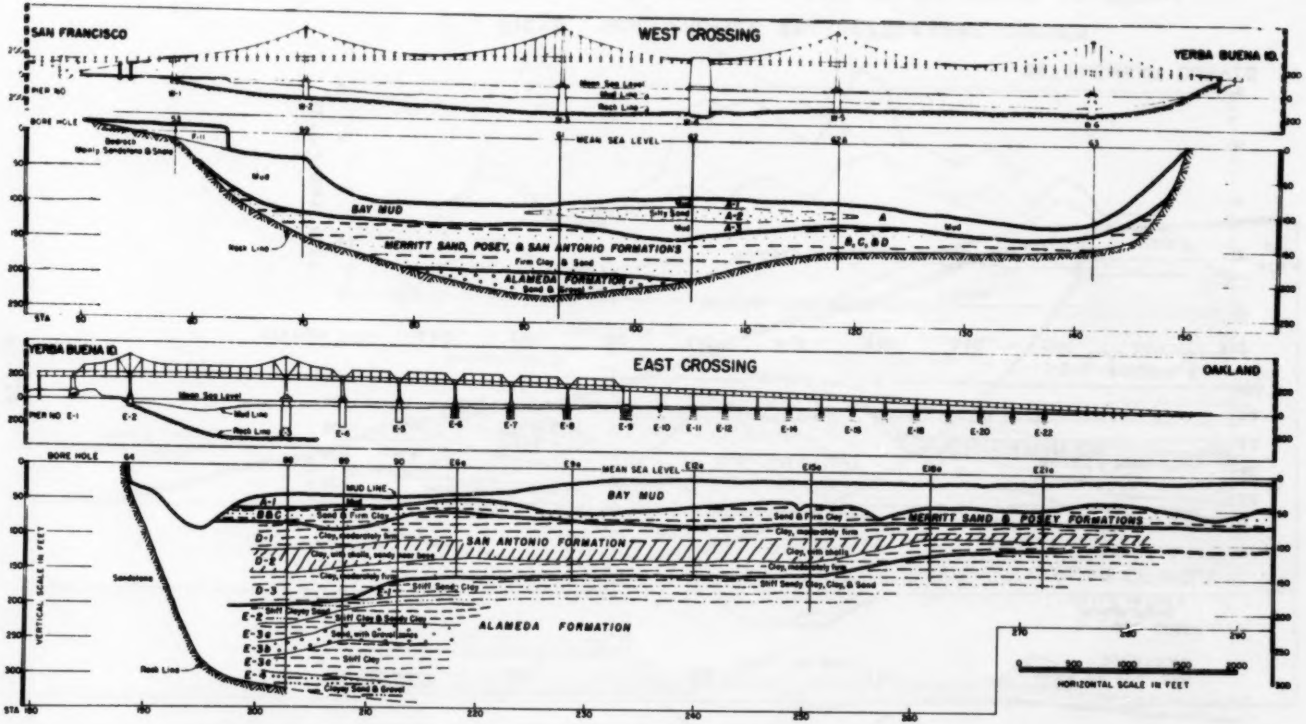

FIG. 4. SOIL PROFILE ALONG SAN FRANCISCO OAKLAND BAY BRIDGE, CALIFORNIA

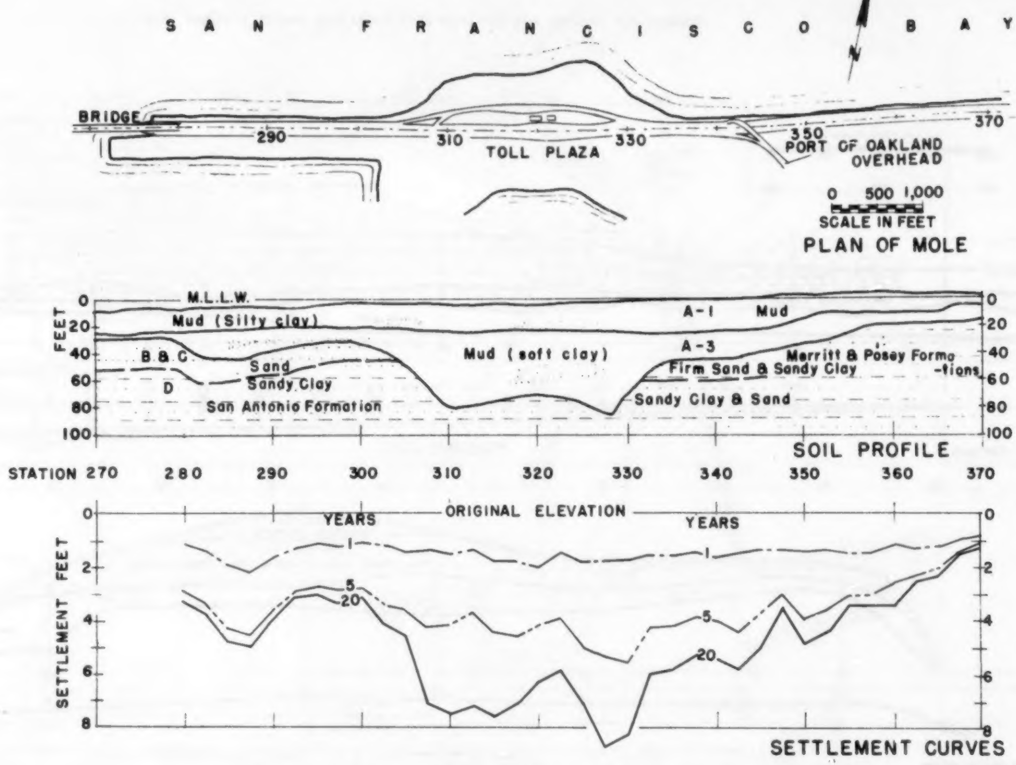

FIG. 5. SOIL PROFILE AND SETTLEMENT CURVES, OAKLAND MOLE, SAN FRANCISCO OAKLAND BAY BRIDGE, CALIFORNIA

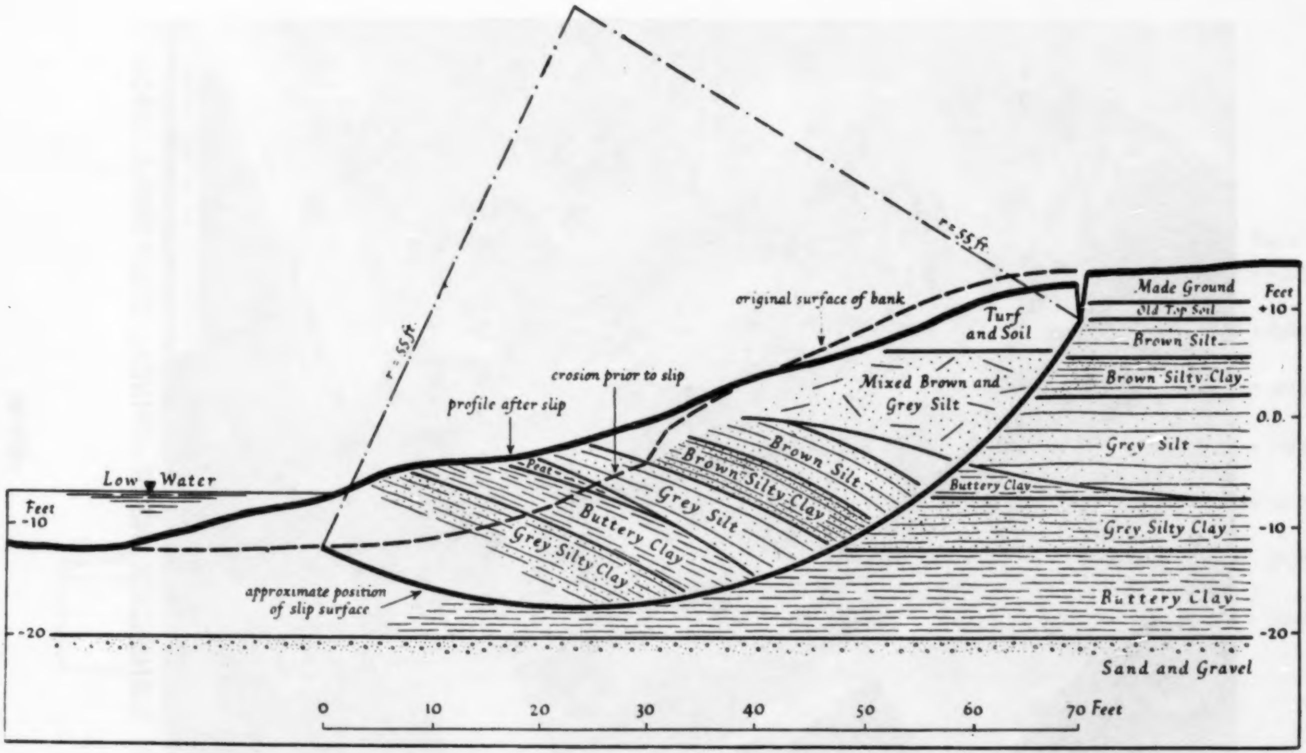

FIG. 6. LANDSLIDE ON BANK OF RIVER OUSE, ENGLAND
(AFTER SKEMPTON)

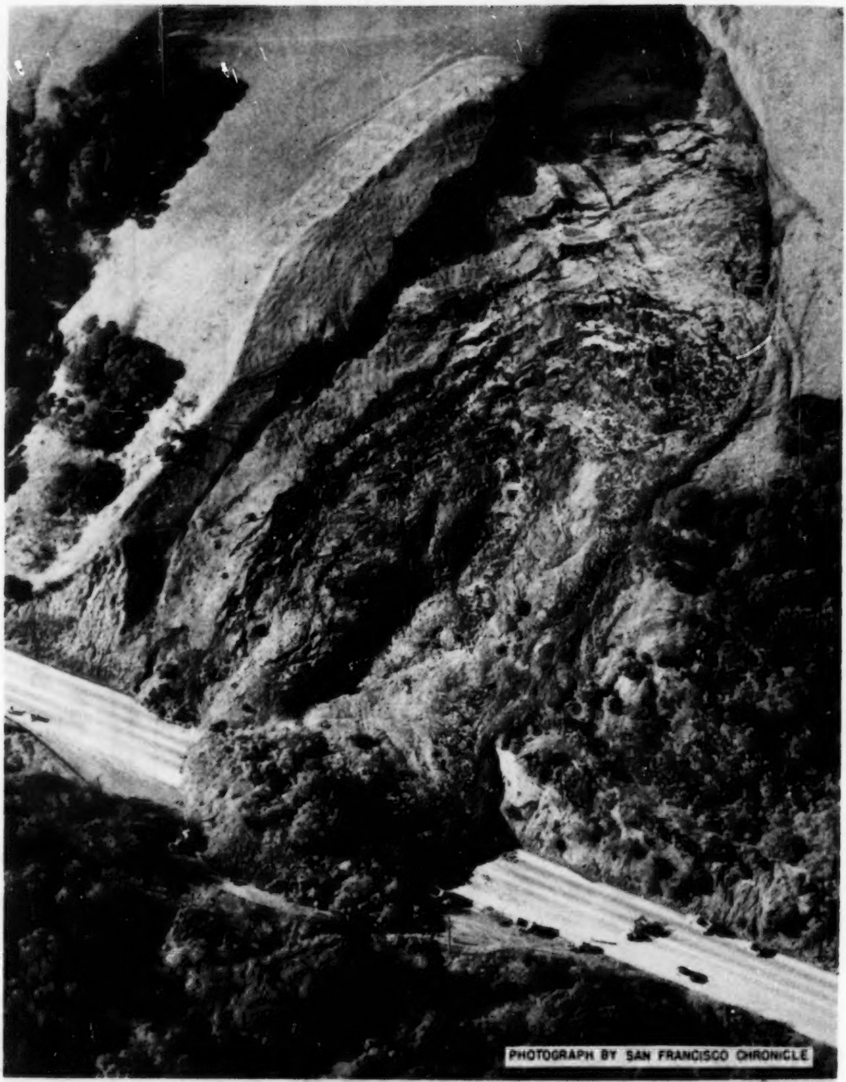

FIG. 7. LANDSLIDE NEAR ORINDA, CALIFORNIA, 1951

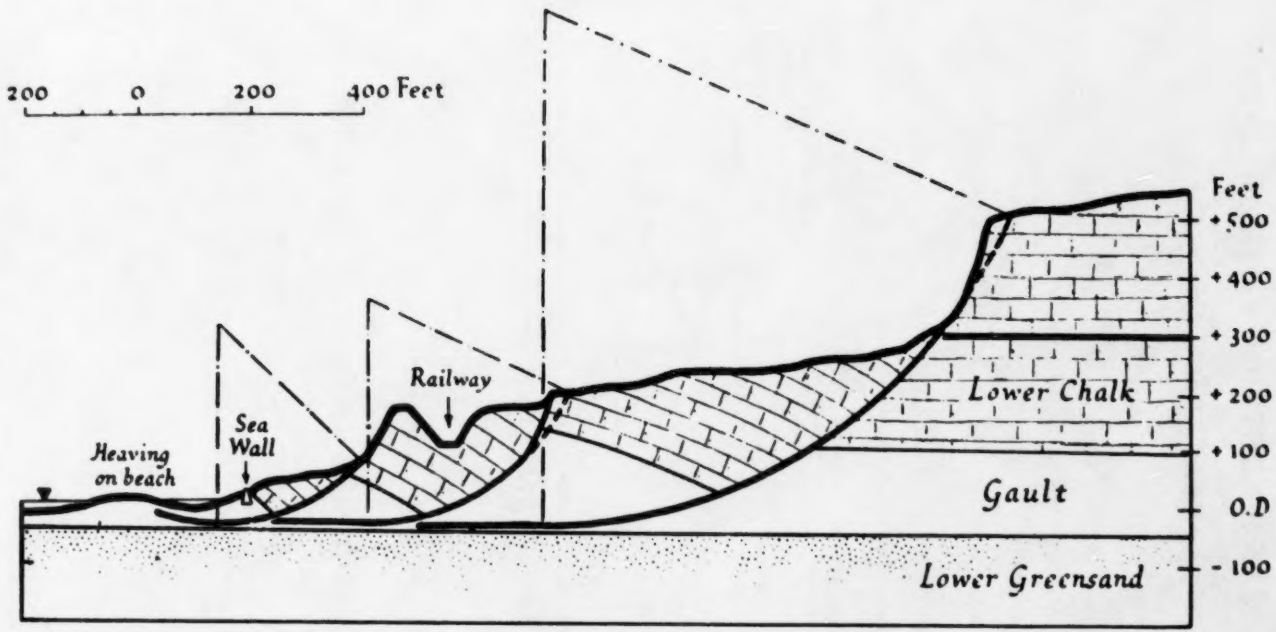

FIG. 8. GENERALIZED SECTION THROUGH FOLKESTONE WARREN, ENGLAND, SHOWING PROBABLE MECHANISM OF LANDSLIDES (AFTER WARD)